PB-214 536

# WATER/RECIPROCATING EXPANDER SYSTEM, PRESENTED AT AUTOMOTIVE RANKINE CYCLE CONTRACTORS COORDINATION MEETING, JANUARY 20-21, 1972

Steam Engine Systems Corporation
Newton, Massachusetts

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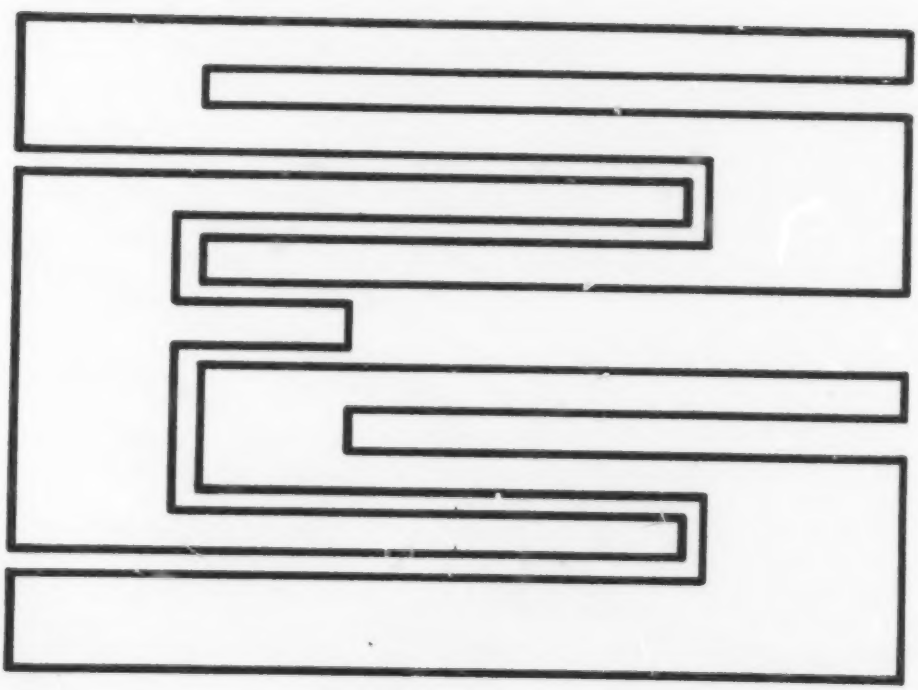


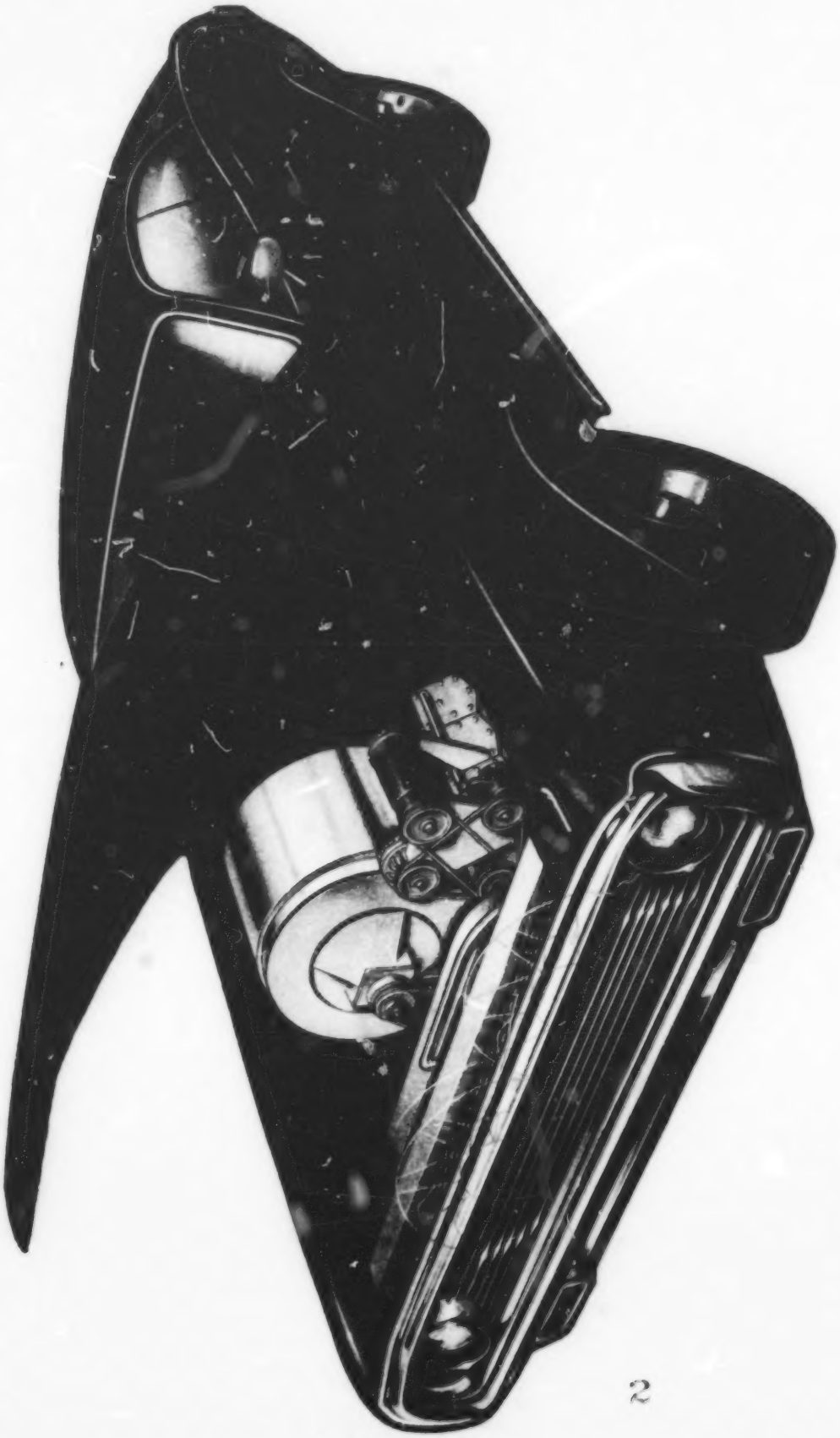
**STEAM ENGINE SYSTEMS CORPORATION**

141 CALIFORNIA STREET NEWTON, MASSACHUSETTS 02158

STEAM ENGINE SYSTEMS CORPORATION

RANKINE CYCLE POWERPLANT

- WATER BASE WORKING FLUID
- RECIPROCATING EXPANDER



## STEAM ENGINE SYSTEMS CORPORATION

WATER BASE RANKINE CYCLE SYSTEM
RECIPROCATING EXPANDER

SES - SYSTEM DEVELOPER

- SYSTEM DESIGN AND DEVELOPMENT
- STEAM GENERATOR DESIGN/DEVELOPMENT
- BURNER DESIGN/DEVELOPMENT
- EXPANDER CONCEPT ANALYSIS/TESTING/DEVELOPMENT
- CONDENSER, FAN, FAN DRIVE DESIGN AND ANALYSIS

MAJOR SUBCONTRACT WORK

RICARDO - EXPANDER DESIGN/FABRICATION

BENDIX - CONTROL SYSTEM ANALYSIS/DESIGN AND DEVELOPMENT

ESSO - EXPANDER LUBRICANT DEVELOPMENT

CHRYSLER- ENGINE DESIGN CRITIQUE, COST STUDY
DESIGN POWERPLANT INSTALLATION IN VEHICLE,
VEHICLE PERFORMANCE ANALYSIS

SES - RANKINE CYCLE SYSTEM CONCEPT

WORKING FLUID - PURE WATER

CYCLE - SIMPLE

STEAM CONDITIONS - 1000°F, 1000 PSIA

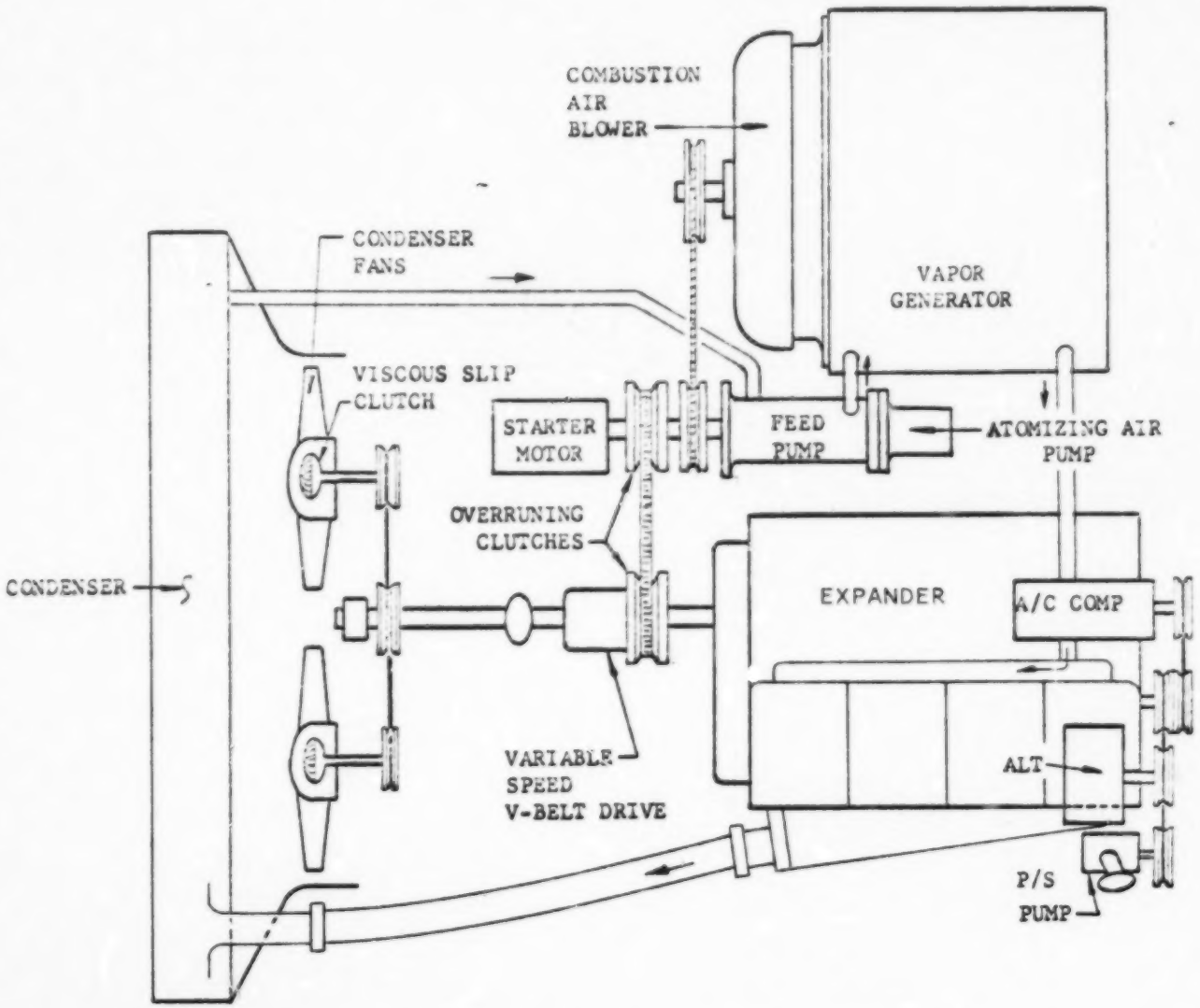
EXPANDER - CONVENTIONAL RECIPROCATING TYPE -
4 CYLINDER IN-LINE,
TRUNK PISTON - UNIFLOW EXHAUST
VARIABLE CUT-OFF CONTROL

COMPACT BURNER / VAPOR GENERATOR

LOW $NO_x$ BURNER

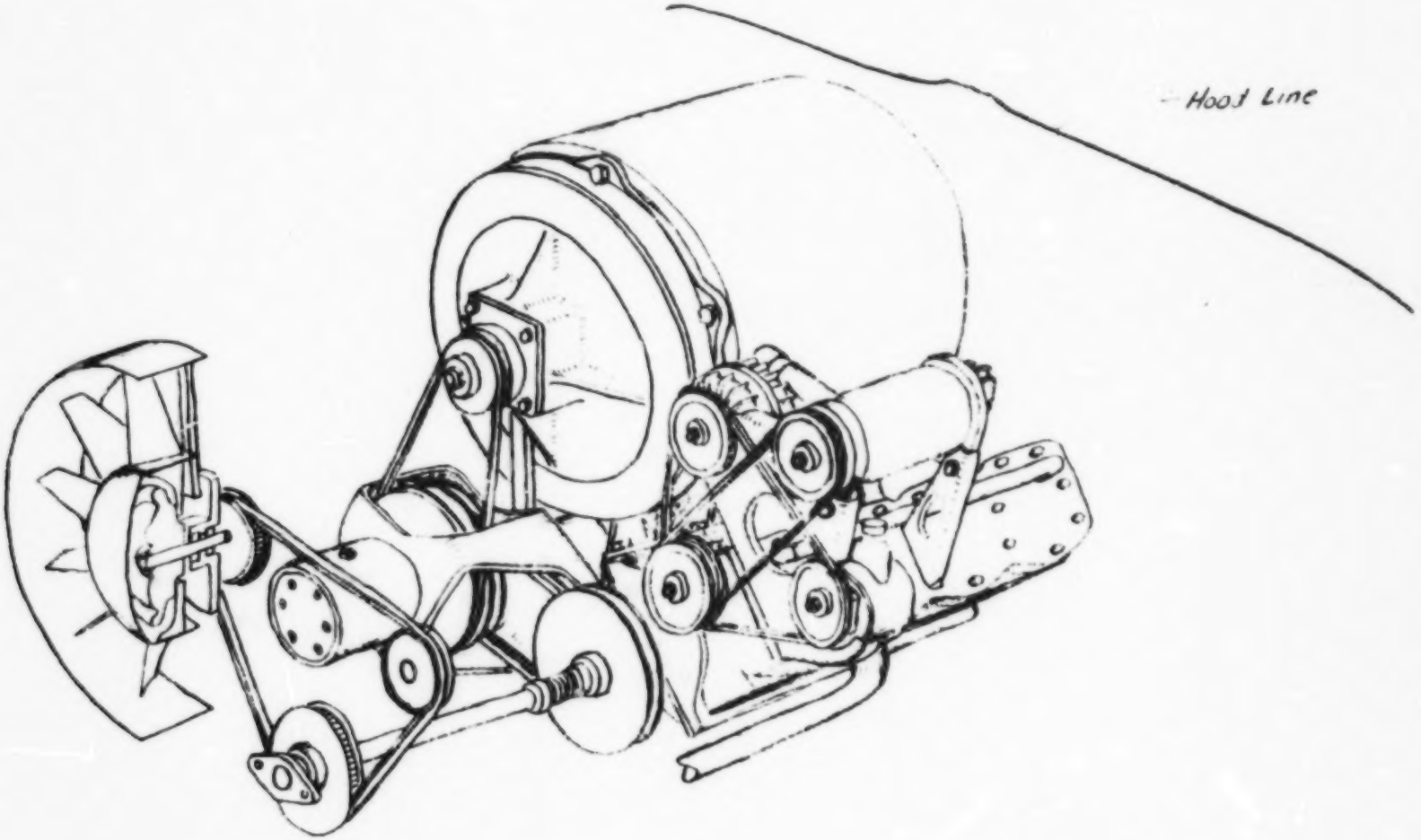
FULLY CONDENSING - FLOATING CONDENSER
PRESSURE - 20 PSIA NOMINAL
FANS DRIVEN THRU VISCOUS SLIP CLUTCH

FREEZE PROTECTION - INSULATED SUMP WITH AUTOMATIC
PILOT HEATER



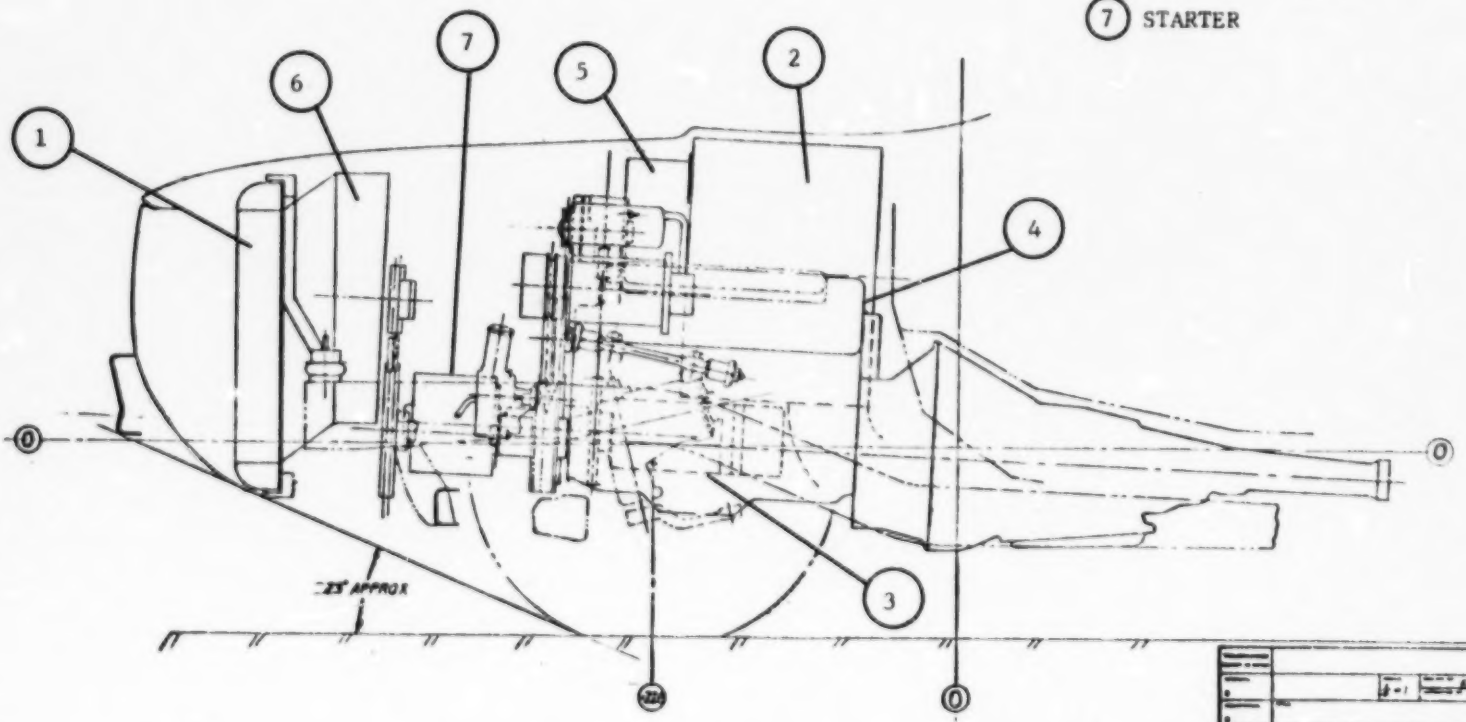

SES POWERPLANT LAYOUT WITH

AUXILIARY AND ACCESSORY DRIVES



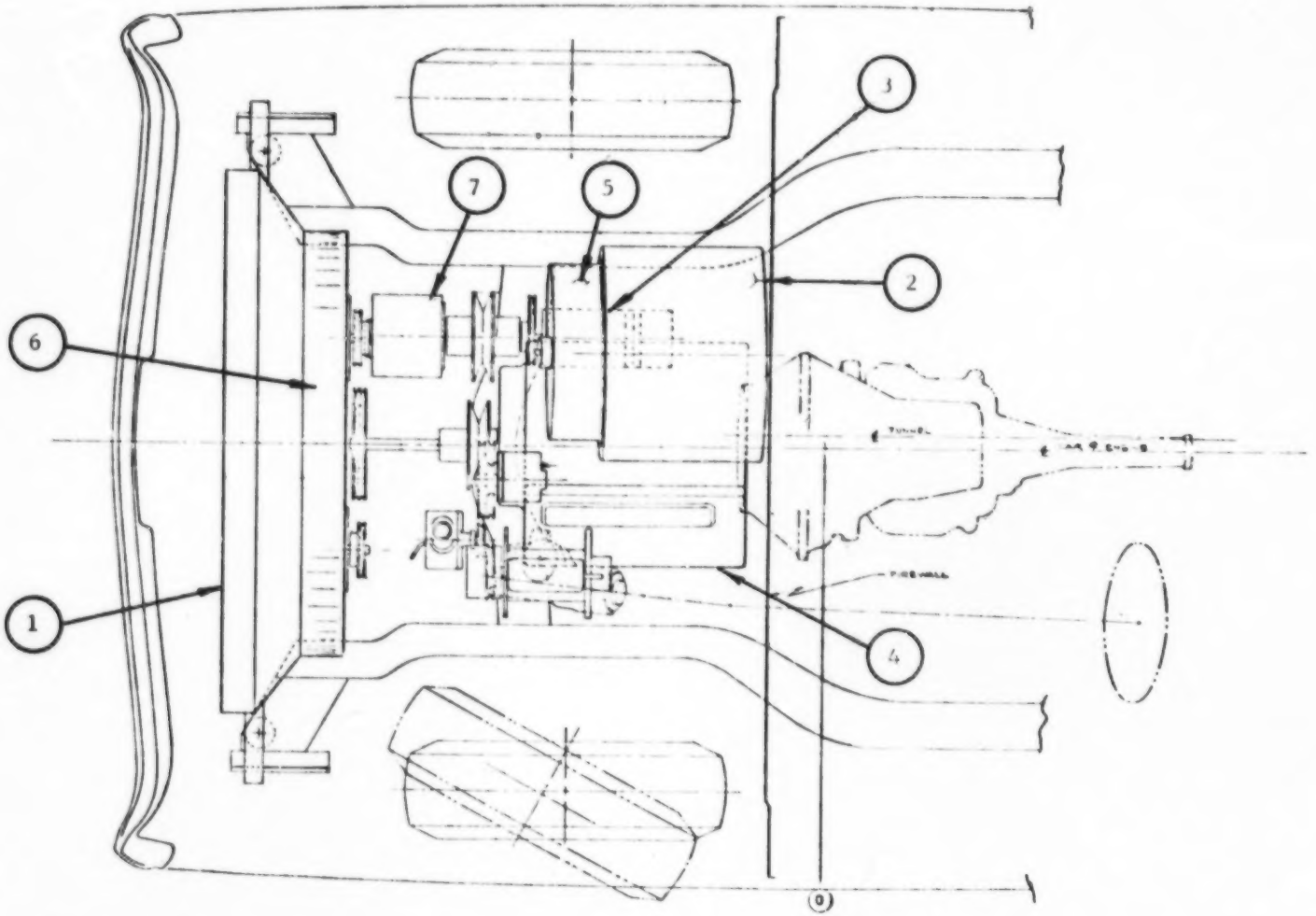

SES POWERPLANT

Side View of Propulsion System in Future Chrysler "C" Body




1. CONDENSER
2. STEAM GENERATOR
3. FEEDWATER PUMP
4. EXPANDER
5. BLOWER
6. CONDENSER FANS
7. STARTER

Top View of Propulsion System in Future Chrysler "C" Body



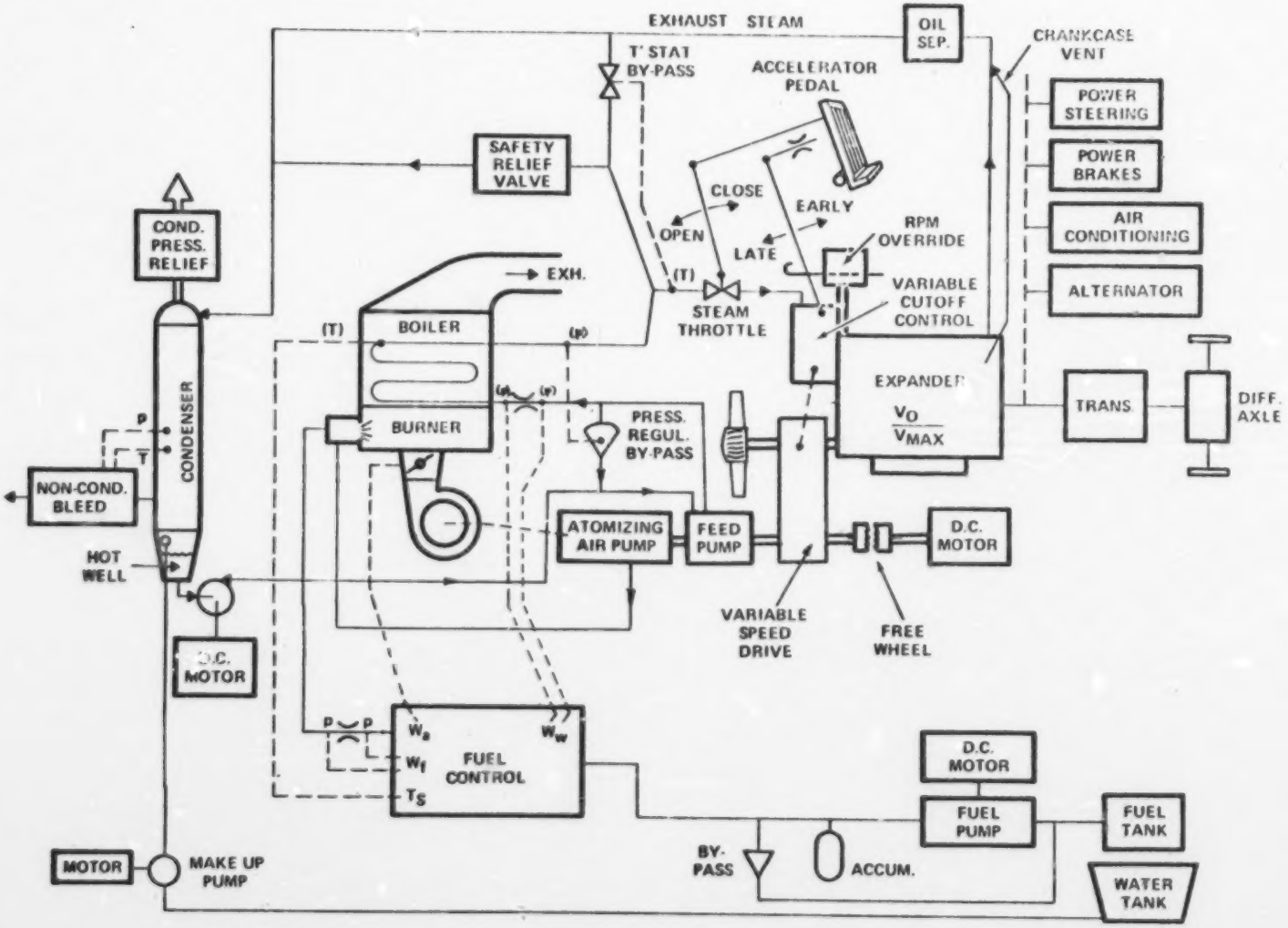

1 CONDENSER
2 STEAM GENERATOR
3 FEEDWATERPUMP
4 EXPANDER
5 BLOWER
6 CONDENSER FANS
7 STARTER

## CONTROLS

### BASIC PHILOSOPHY

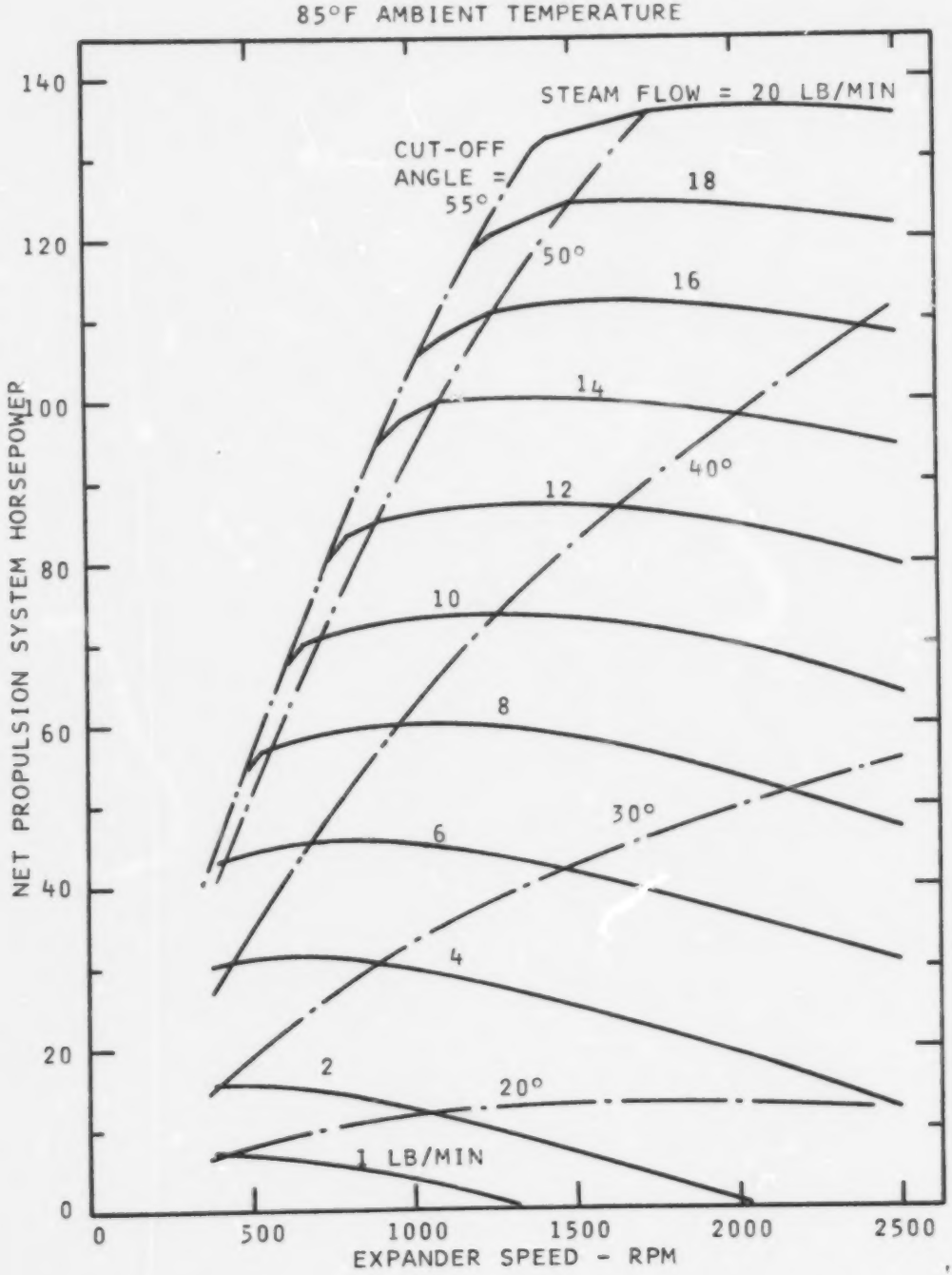
- POWER MODULATION BY DRIVER CONTROL OF EXPANDER INTAKE VALVE CUT-OFF
- BURNER/BOILER MAINTAINS SUPPLY OF STEAM AT CONSTANT PRESSURE AND TEMPERATURE AUTOMATICALLY
  - ANTICIPATORY CONTROL OF FEEDPUMP AND COMBUSTION AIR BLOWER OUTPUT FOR FAST RESPONSE
  - FEEDBACK TRIM CONTROL TO ADJUST FOR PRESSURE AND TEMPERATURE ERRORS
- CONDENSER FANS AND SHUTTERS CONTROLLED AUTOMATICALLY
- AUTOMATIC START-UP AND SHUTDOWN SEQUENCING CONTROLS FOR FREEZE PROTECTION
- AUTOMATIC SAFETY CONTROLS

# METERING CONTROL SYSTEM SYSTEM SCHEMATIC



## NET SYSTEM HORSEPOWER

NET POWER AFTER ALL AUXILIARIES
VEHICLE IN HIGH GEAR
85°F AMBIENT TEMPERATURE



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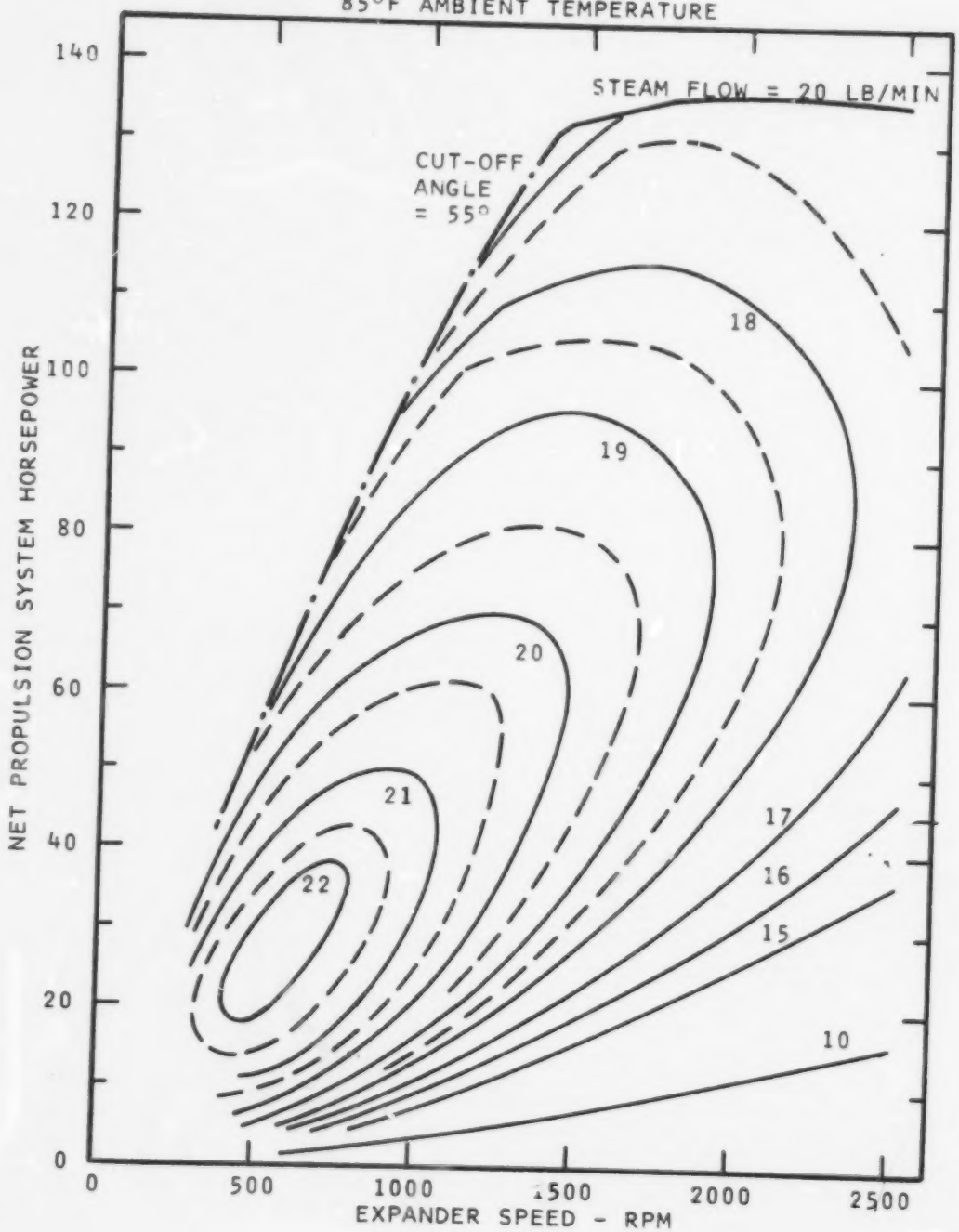
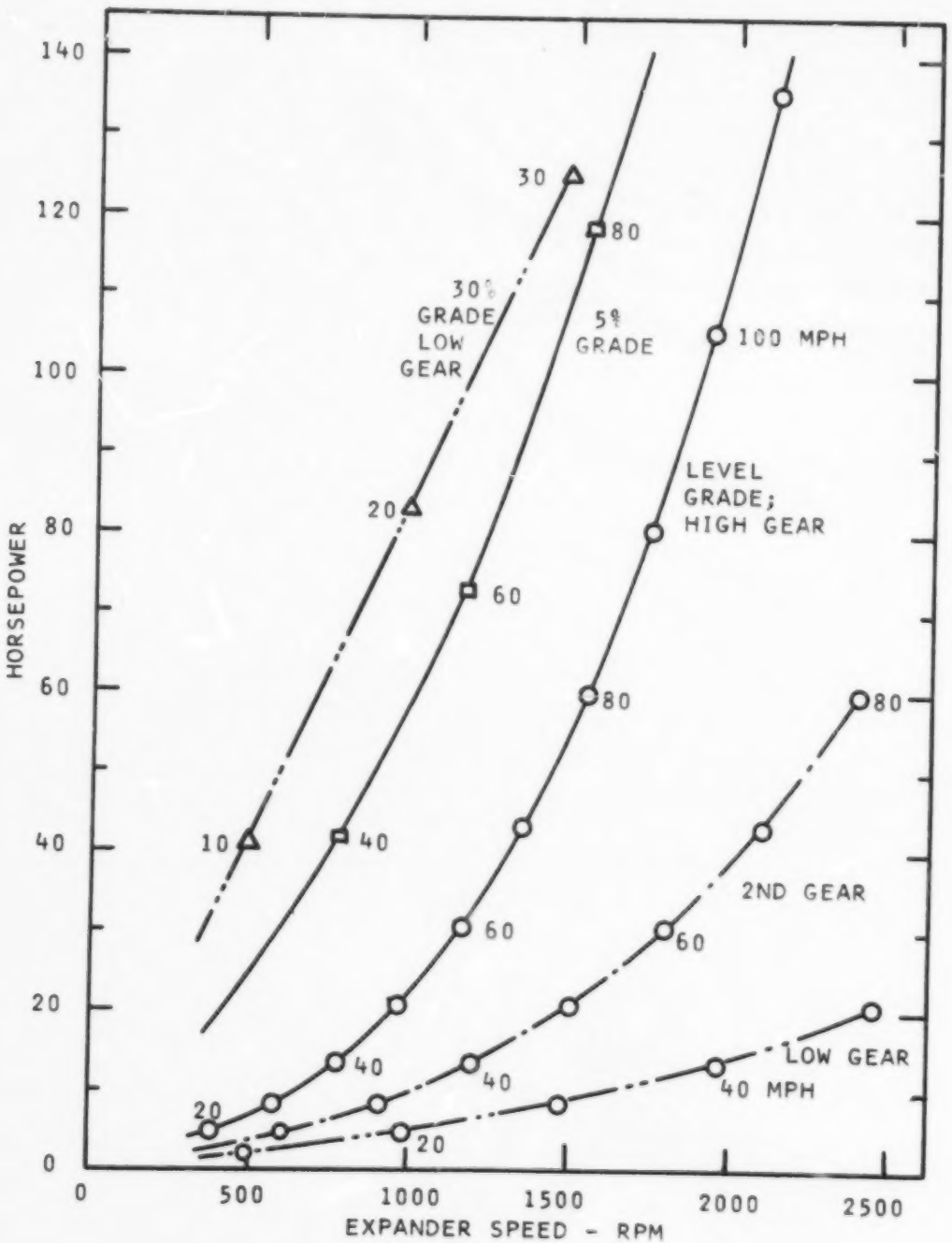
## COUNTOURS OF SYSTEM THERMAL EFFICIENCY

NET POWER AFTER ALL AUXILIARIES
VEHICLE IN HIGH GEAR
85°F AMBIENT TEMPERATURE



VEHICLE ROAD LOAD REQUIREMENTS



## VEHICLE PERFORMANCE

SES RANKINE CYCLE PROPULSION SYSTEM
140 CID EXPANDER - SERIES POPPET VALVES, 55° MAXIMUM CUT-OFF, 20 LB/MIN MAXIMUM FLOW

| CASE | STANDING START | | 25-70 MPH | HIGH SPEED PASS | | MAXIMUM SPEED (MPH) | | MAXIMUM GRADE |
|---|---|---|---|---|---|---|---|---|
| | TIME 440 FT (SEC) | TIME 0-60 MPH (SEC) | TIME (SEC) | TIME (SEC) | DISTANCE (FT) | 4600 LB ON 0% GRADE | 5100 LB ON 5% GRADE | 5100 LB @ 15 MPH |
| EPA GOAL @ 85°F | 10 | 13.5 | 15 | 15 | 1400 | 85 | 70 | 30 |
| 85°F AMBIENT | | | | | | | | |
| STANDARD TRANSMISSION | 9.85 | 11.60 | 11.75 | 11.4 | 1109 | 110 | 86.5 | 31.3 |
| AUTOMATIC TRANSMISSION | 9.84 | 11.92 | 12.27 | 11.6 | 1125 | 109 | 84.6 | 35 |
| 105°F AMBIENT | | | | | | | | |
| STANDARD TRANSMISSION | 10.18 | 12.70 | 12.9 | 11.9 | 1145 | 111 | 85.0 | 28.3 |
| AUTOMATIC TRANSMISSION | 10.05 | 12.86 | 13.5 | 12.1 | 1161 | 110 | 83.5 | 31 |



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FUEL ECONOMY - THERMAL EFFICIENCY

IN-LINE 4 EXPANDER - SERIES POPPET VALVE
PERFORMANCE AT CONSTANT SPEED, LEVEL GRADE, STILL AIR 85°F AMBIENT

| VEHICLE VELOCITY (MPH) | MANUAL TRANSMISSION | | AUTOMATIC TRANSMISSION | |
|---|---|---|---|---|
| | EFFICIENCY BTU/MI | ECONOMY MPG | EFFICIENCY BTU/MI | ECONOMY MPG |
| 20 | 4570 | 28.0 | 4640 | 27.6 |
| 30 | 4260 | 30.0 | 4470 | 28.6 |
| 40 | 4850 | 26.4 | 4980 | 25.7 |
| 50 | 5740 | 22.3 | 5900 | 21.7 |
| 60 | 6870 | 18.6 | 7040 | 18.2 |
| 70 | 8380 | 15.2 | 8580 | 14.9 |
| 80 | 10090 | 12.7 | 10290 | 12.4 |

NOTES; BASED ON GASOLINE (127,900 BTU/GAL)

ACCESSORY LOAD OF 2 HP



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## TEST CONDITIONS & DATA - SES V-4

SPEEDS TO 2750 RPM

STEAM PRESSURES TO 750 PSIA

STEAM TEMPERATURES TO 950°F

TOTAL RUNNING HOURS WITH STEAM 104.8 HOURS

MAXIMUM POWER OUTPUT TO DATE (UNDER STEADY-STATE CONDITIONS)

MEASURED BPH = 50 HP IHP = 65 HP

AT CONDITIONS

580 PSIA STEAM PRESSURE

800°F STEAM TEMPERATURE

17 PSIA EXHAUST PRESSURE

1500 RPM

ALPHA = 10°

## CONCLUSIONS BASED ON PRELIMINARY SES V-4 TESTING

1) UNIFLOW TRUNK PISTON EXPANDER DESIGN IS SUITABLE FOR AN AUTOMOTIVE POWERPLANT
   - economical high volume production capability
   - sufficient expansion available in a simple expander

2) CRANKCASE SPLASH LUBRICATION OF CYLINDER WALLS ADEQUATE
   - maximum measured cylinder wall temperature at top ring was approximately equal to 500°F with inlet steam temperature at 950°F (comparable to diesel wall temperatures)
   - upper cylinder wall temperature is sufficiently high to prevent condensation losses
   - no lubricant degradation products behind piston rings

3) LOW COST CRANKCASE LUBRICATING OIL FORMULATIONS ARE SUITABLE FOR STEAM EXPANDER LUBRICATION
   - lube must be compatible with water
   - non-emulsion forming type is required
   - crankcase lubricant sump temperature maintained at temperatures above water boiling point
   - condensation and blow-by water/steam entering crankcase are boiled off and sent to condenser

4) ADEQUATE 'BREATHING' - WITH A POPPET VALVE SYSTEM
   - adequate filling of the cylinder at high expander speeds
   - an inexpensive valve train (similar to present automotive practise ; bucket type tappets) can be designed to function properly even under high gas (steam) pressures

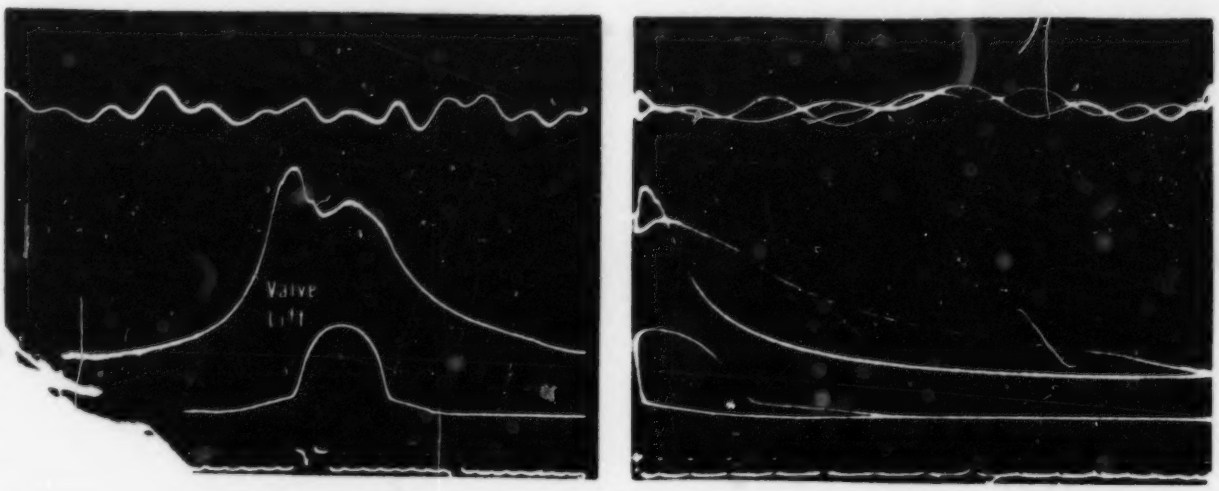
5) CHARACTERISTICS OF F.H.P. DETERMINED
   - computer predictions of F.H.P. varies with R.P.M.
   - testing indicates that F.H.P. is more sensitive to changes in M.E.P. than R.P.M.

6) EVALUATION OF CANDIDATE LUBRICANTS
   - reference lube; requires better demulsibility and rust protection capability
   - new lubricant formulation (based on ESSO rig tests) being evaluated

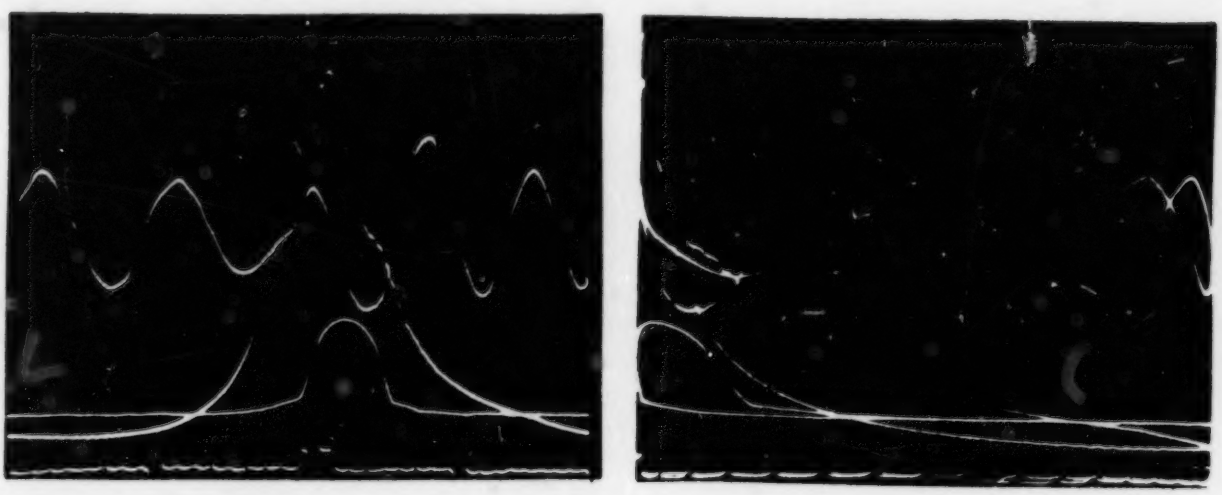
7) SUPPLY STEAM PRESSURE CYCLING PROBLEM
   - pressure fluctuations at inlet valve
   - results in poor breathing under certain conditions

Pressure vs. Crank Angle

Pressure vs. Piston Lift




1000 RPM; 300 psi, 800°F Inlet Steam; Alpha = 10°



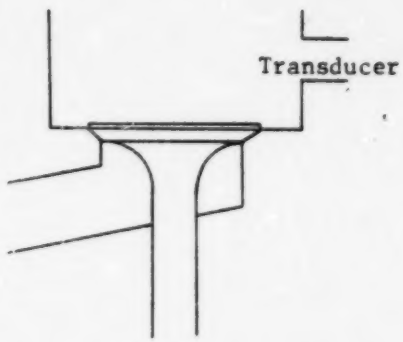
2500 RPM; 550 psi, 800°F Inlet Steam; Alpha = 10°

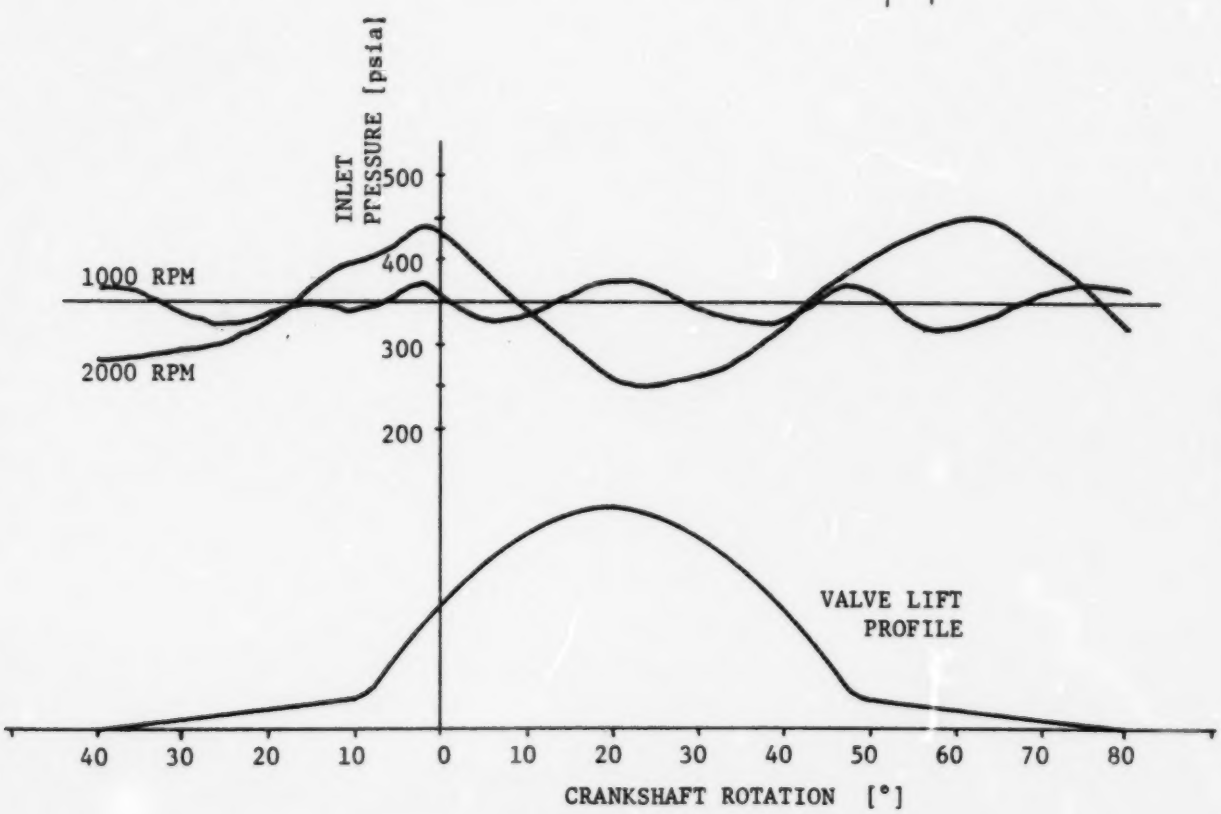
PRESSURE TRACES RECORDED UPSTREAM AND DOWNSTREAM OF THE ADMISSION VALVE

SES V-4 PRESSURE FLUCTUATION IN THE END OF THE INLET MANIFOLD

Steam conditions: Ti = 800°F pi = 350 psia

Admition period: 50° + 30°RAMP



## SES V-4 PERFORMANCE DATA

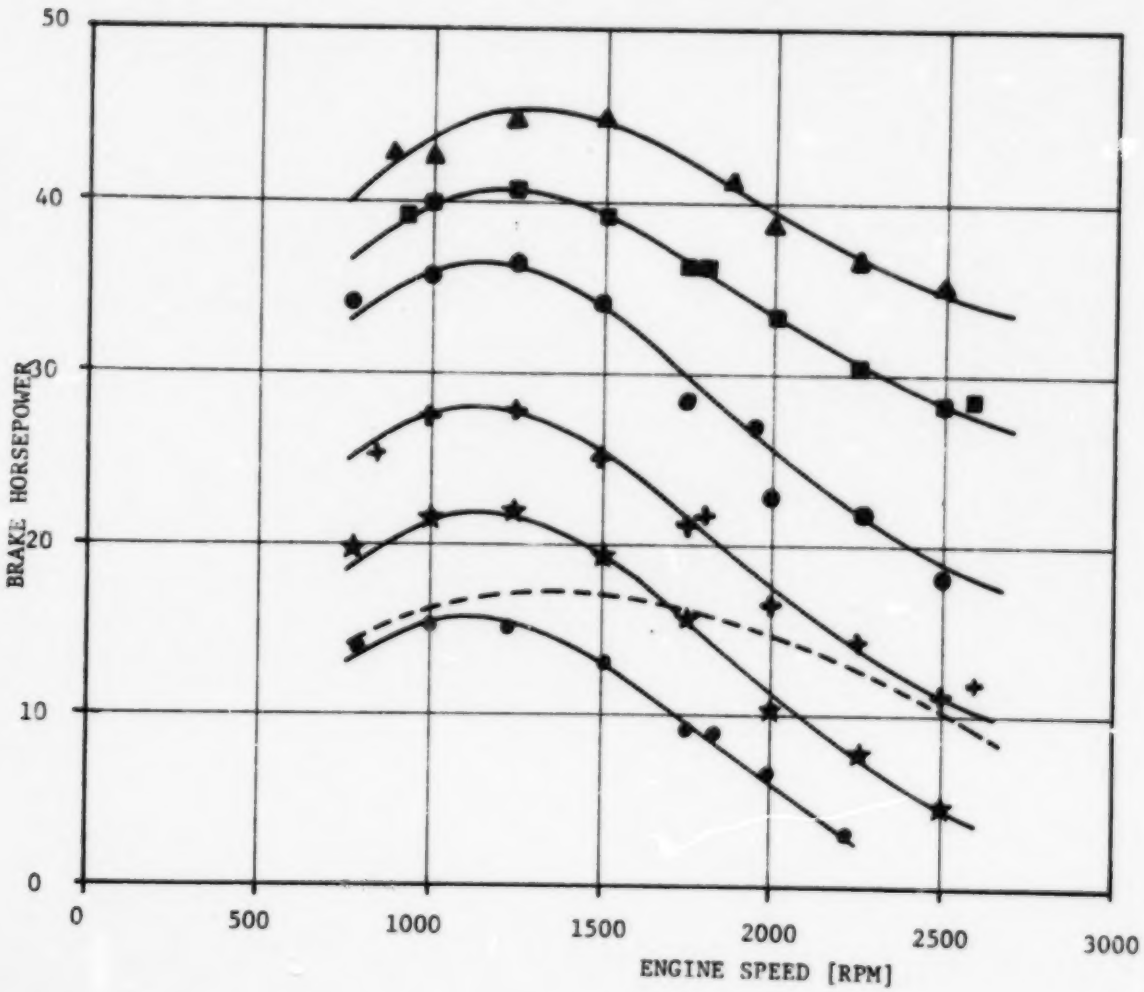
Steam conditions in the inlet manifold:

Ti = 800°F

pi : ● 300 psia
★ 350 psia
✚ 400 psia
● 450 psia
■ 500 psia
▲ 550 psia

----- computer prediction

Admission period: 50° + 30° RAMP



## LUBRICANT PROGRAM (ESSO)

### PROGRAM OBJECTIVE

- define lubricant requirements for a steam engine (1000°F)
- formulate lubricants for use in SES steam engine.

### STRATEGY

- formulate a reference lube based on initial definition of conditions
- characterize the reference lube behavior in laboratory tests and correlate with SES engine test results
- formulate a premium lube for SES engine based on laboratory tests ( final evaluation in SES engine )

### LUBRICANT SCREENING TESTS

- Modified ER & E Lube Stability test
- Panel Coker test
- Thermal Gravimetric Analysis
- Emulsion Characteristic test
- Shell 4-Ball (EP) test

### BASE STOCK PARAMETERS INVESTIGATED

- Base stock types ; paraffinic & napthenic
- Refining processes ; nonhydrofined , hydrofined , acid treated super refined

### CONCLUSIONS - 18 BASE STOCKS EVALUATED -(OXIDATION STABILITY)

- highly treated base stocks;e.g.acid treated distillates and severly refined residua have poor oxidation stability.
- hydrofined base stocks are more stable than those produced without hydrofining.
- mixtures of distillates and residua (Bright Stocks) have better oxidation stability than do distillates alone.
- paraffinics are superior to napthenics

### 4 BASE STOCKS WERE SELECTED FOR FURTHER EVALUATION WITH ADDITIVES

- oxidation inhibitors
- EP agents
- rust inhibitors

### CONCLUSIONS

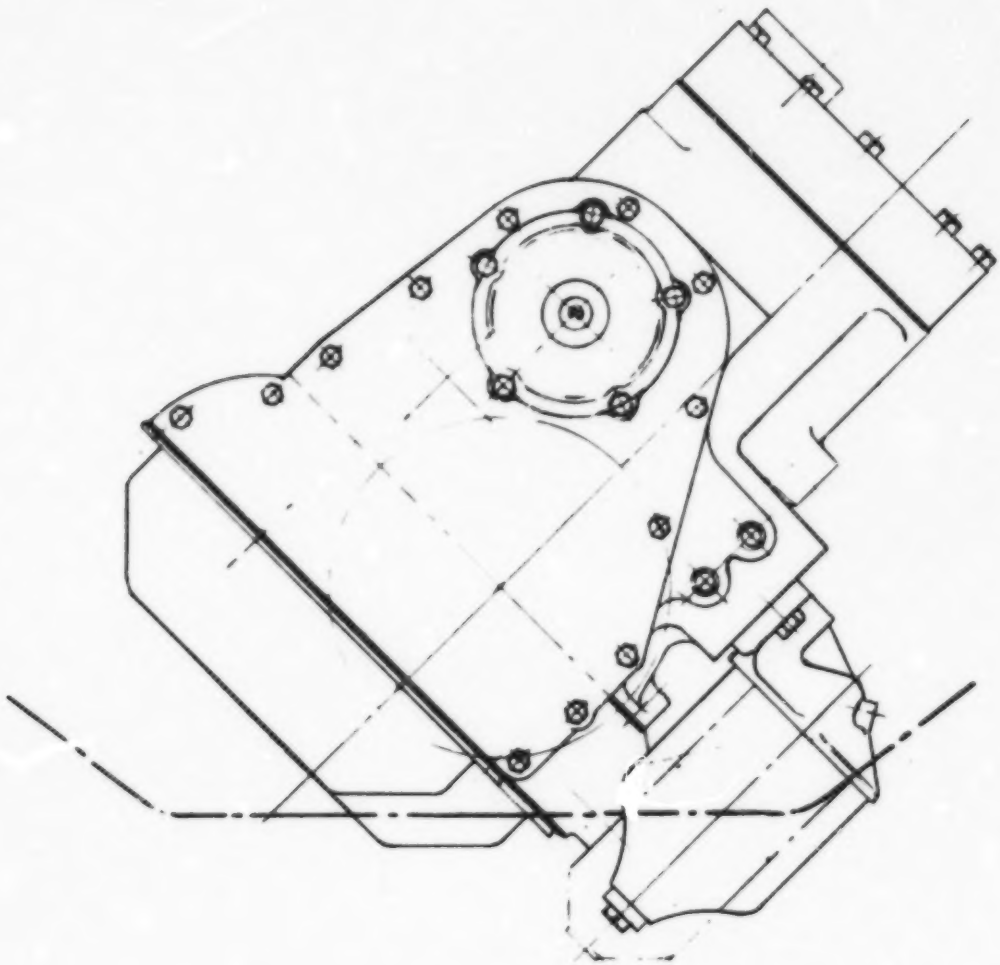
- inhibited blends of hydrofined paraffinic distillates and residua are the most suitable base stocks
- hindered phenol (Ethyl 702) type of antioxidants were more effective in paraffinic base stocks
- tricresyl phosphate and hindered phenol additive package was the most suitable antiwear and antioxidant combination
- ester type of rust inhibitor preferred (tentative)

## REFERENCE LUBRICANT ( 480-98-1)

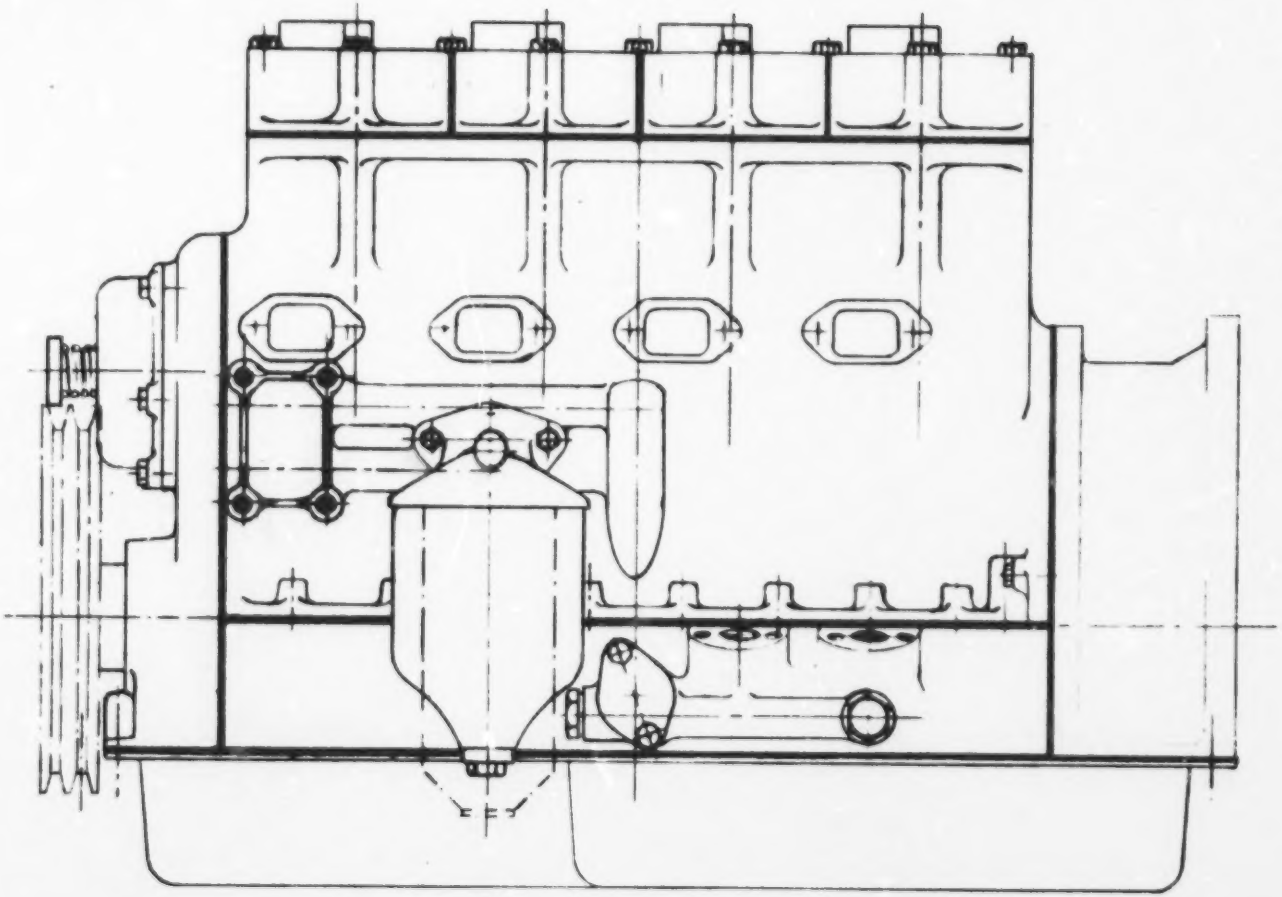
| | | |
|---|---|---|
| PARAFFINIC BASE STOCK - | DISTILLATE .... | 75.2 % |
| | - RESIDUUM ..... | 23.7 % |
| Z D D P EP ADDITIVE | ..... | 1.0 % |
| ESTER TYPE RUST INHIBITOR | ..... | 0.1 % |
| ANTI-FOAM AGENT (DOW CORNING 200 ) | ..... | 30 PPM |

## CANDIDATE LUBRICANT FORMULATION (2415-50-1)

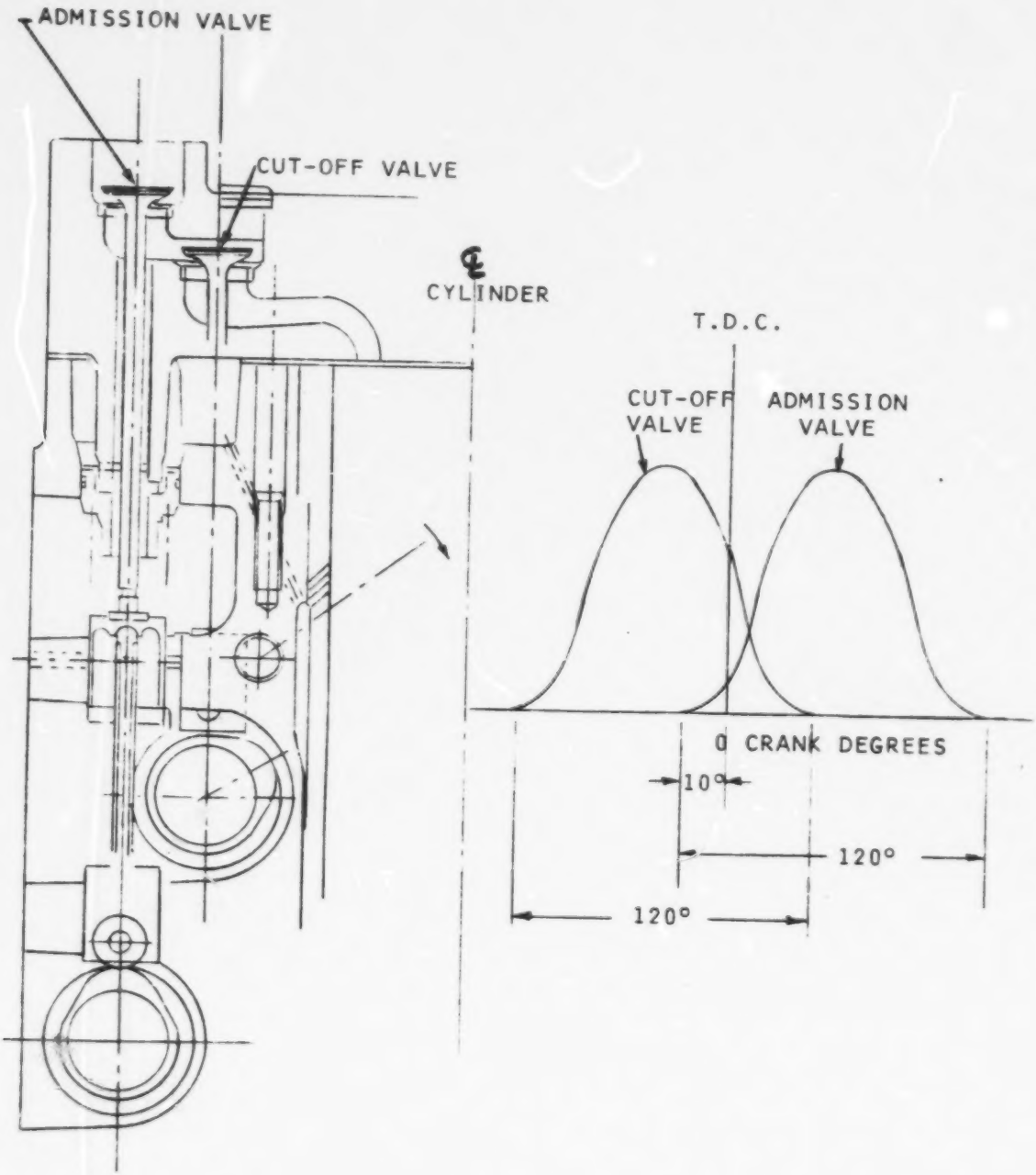
| | | |
|---|---|---|
| HYDROFINED PARAFFINIC DISTILLATE (BAROSA 56) | ... | 58.7 % |
| HYDROFINED PARAFFINIC RESIDUUM (2501) | ..... | 39.0 % |
| HINDERED PHENOL TYPE ANTIOXIDANT | ..... | 1.0 % |
| T.C.P., EP AGENT | ..... | 1.0 % |
| ENJ-1031 , RUST INHIBITOR | ..... | 0.3 % |
| ANTI-FOAM , DC 200 | ..... | 30 PPM |



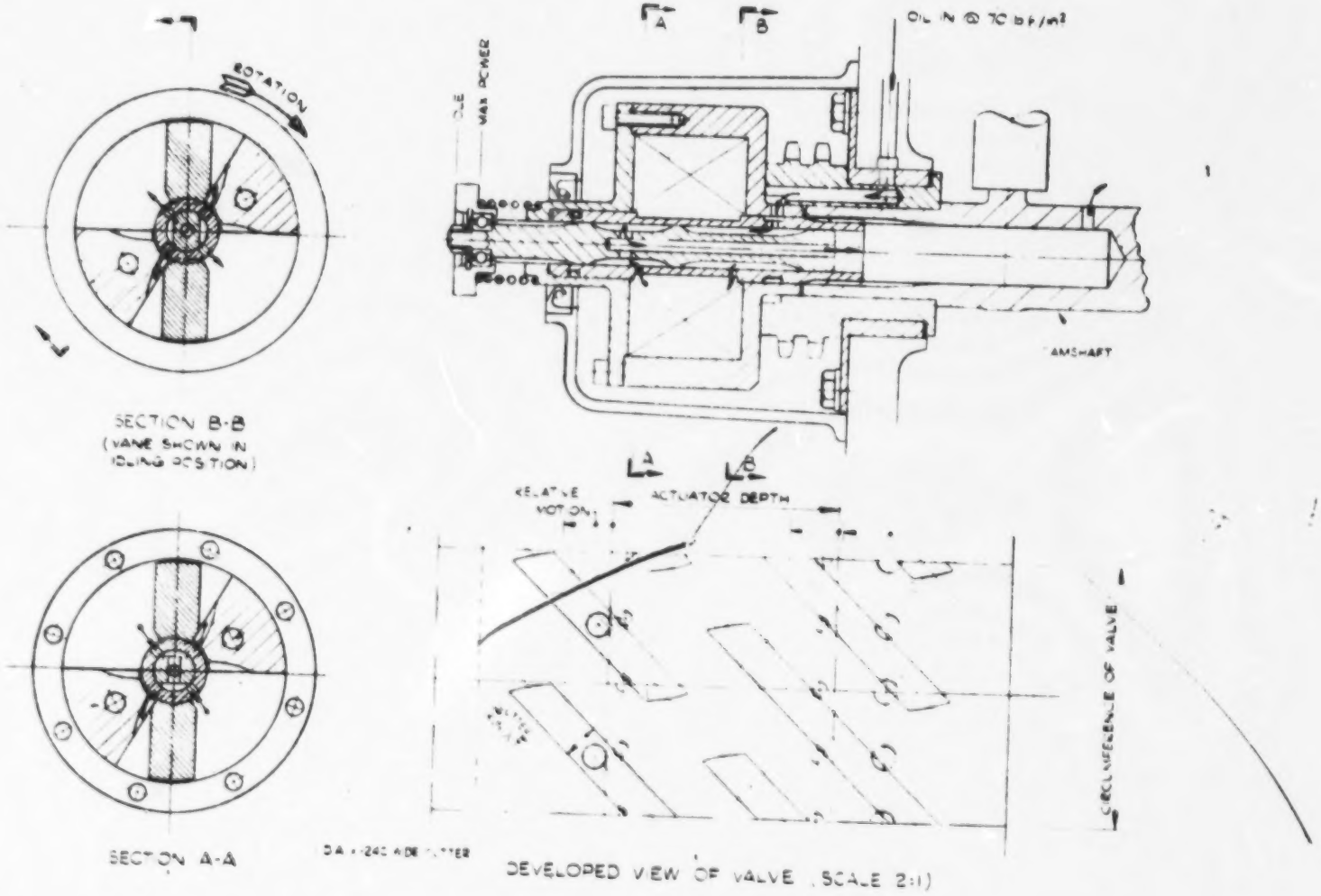
EXPANDER ASSEMBLY-FRONT VIEW



EXPANDER ASSEMBLY-SIDE VIEW




SERIES POPPET VALVES - INLET




# HYDRAULIC ROTARY PHASE - CHANGE MECHANISM

## CONDENSING SYSTEM

19" X 49" X 3.4" CONDENSER (6.46 SQ. FT.)

AIRESEARCH PERFORATED PLATE-FIN CORE
22R-.400-PERF(-13)-.004(AL)

TWIN 19" AXIAL FANS

EATON VISCOUS SLIP CLUTCH FAN DRIVE

20 PSIA CONTROL POINT (228°F)

### DESIGN CONSIDERATIONS

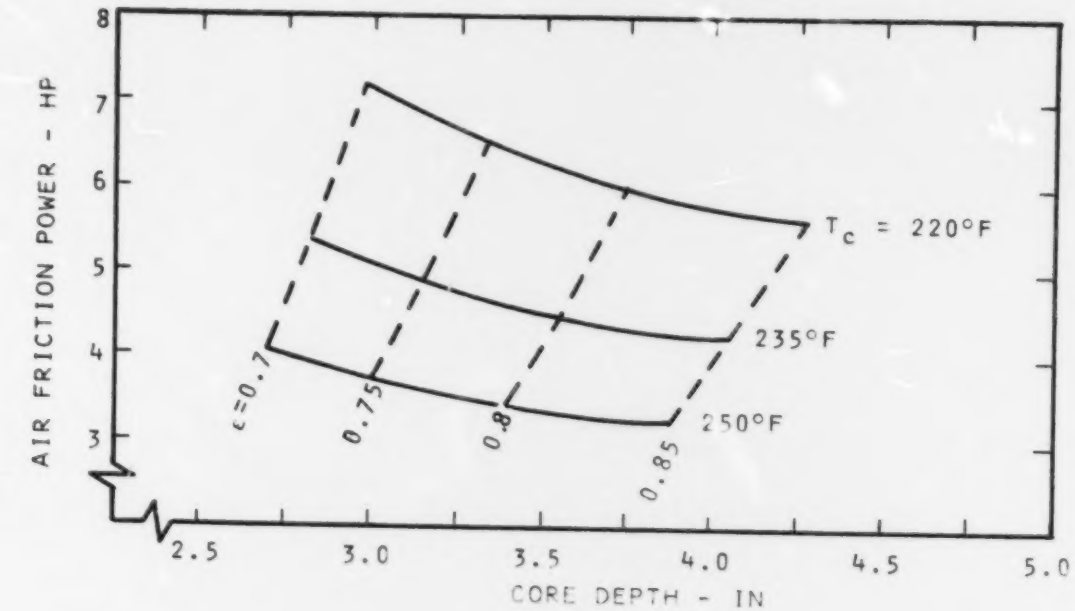
- CONDENSER DESIGN OPTIMIZED FOR MINIMUM FAN POWER AT MAXIMUM STEAM FLOW
- FANS DESIGNED FOR 20 PSIA CONDENSER PRESSURE AT MAXIMUM STEAM FLOW IN HIGH GEAR
- CONDENSER PRESSURE ALLOWED TO RISE TO 34 PSIA AT MAXIMUM STEAM FLOW IN LOW GEAR (THIS IS THE CRITICAL DESIGN POINT)

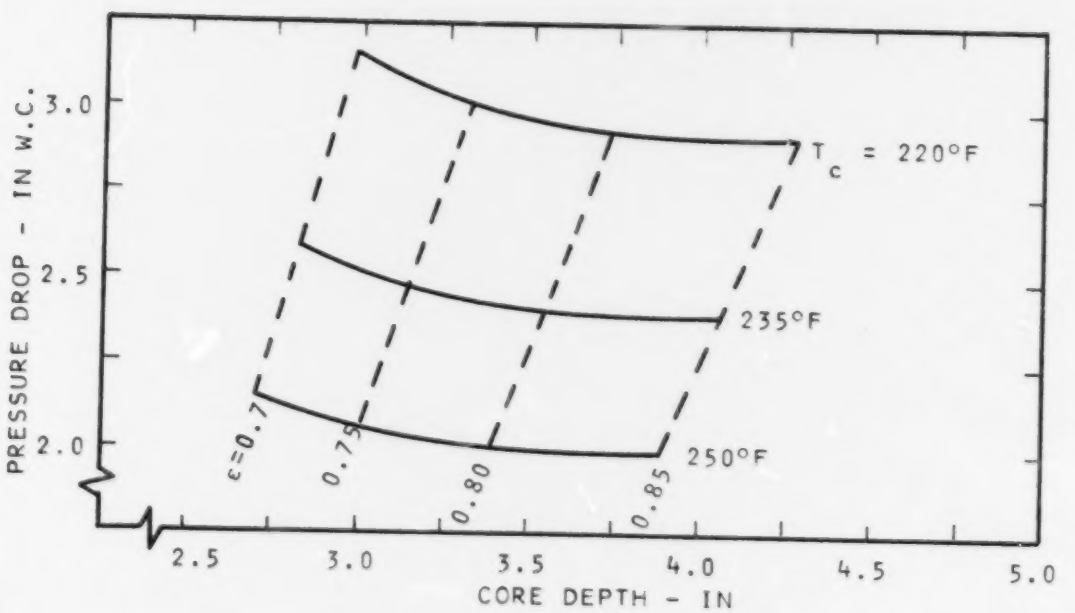
### EFFECTS OF DESIGN POINT CHOICE

| | | |
|---|---|---|
| • MAXIMUM PRESSURE[1] | 20 PSIA | 34 PSIA |
| • MAXIMUM ENGAGED FAN POWER[2] | 27.2 HP | 14.4 HP |
| • MAXIMUM DISENGAGED FAN POWER | 8.5 HP | 4.5 HP |
| • MAXIMUM NET SYSTEM POWER[3] | 133.3 HP | 136.5 HP |
| • FUEL ECONOMY AT 30 MPH [4] | 28.3 MPG | 29.0 MPG |

---

[1] AT 1200 LB/HR, LOW GEAR, 32 MPH, 85°F AMBIENT
[2] IN LOW GEAR, 50 MPH, 125°F AMBIENT
[3] HIGH GEAR, 85°F AMBIENT
[4] MANUAL TRANSMISSION

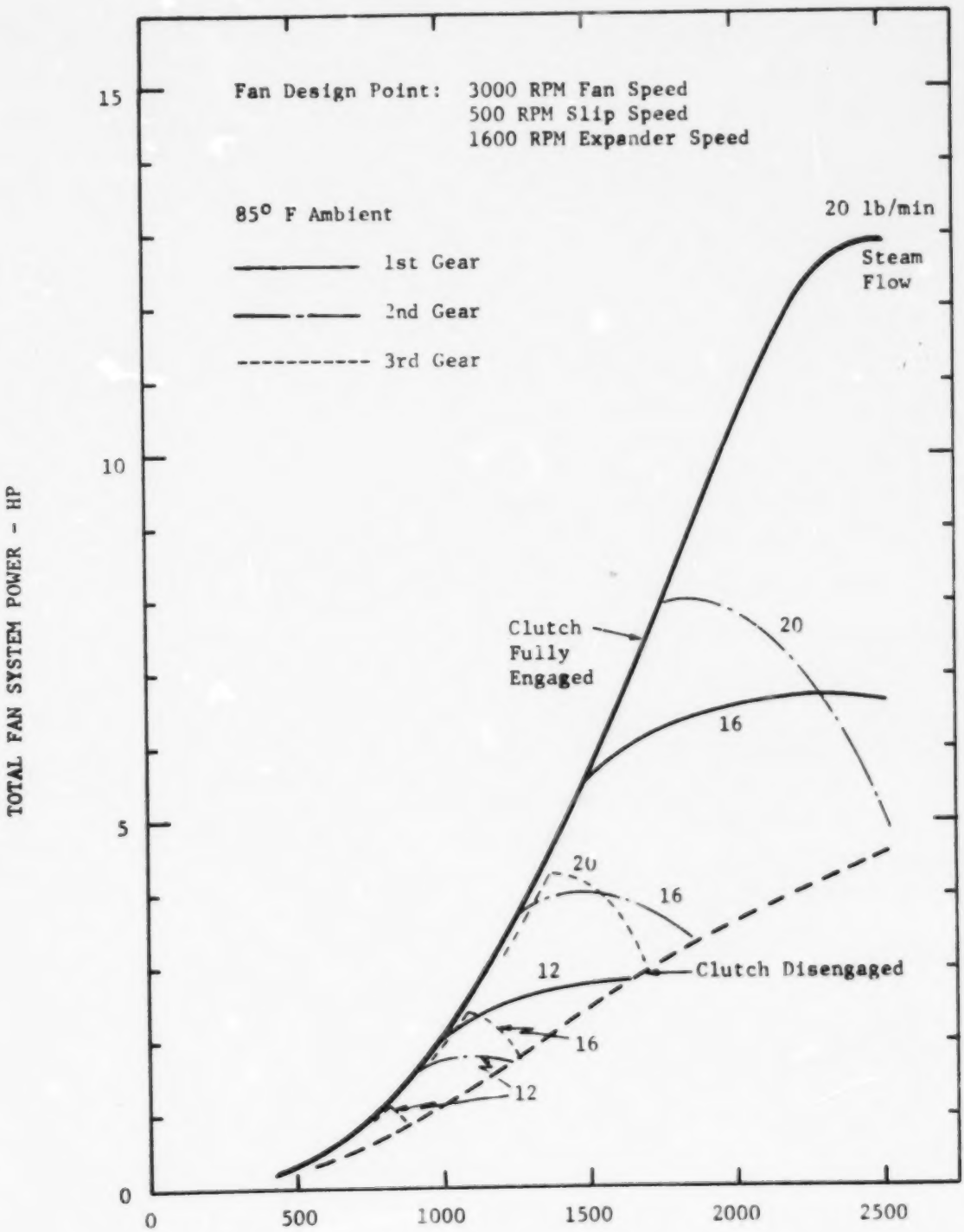



EFFECT OF CONDENSING TEMPERATURE ON AIR-FRICTION POWER AND PRESSURE DROP. SURFACE 22R-.400-PERF(-13)-.004(AL)

$\sigma$ = 0.76, $T_{amb}$ = 85°F, Q = 1.21 X $10^6$ BTU/HR, $A_{fr}$ = 6.46 $FT^2$

FAN POWER VS. EXPANDER SPEED



## BURNER/VAPOR GENERATOR

### OBJECTIVES

#### BURNER

- LOW EMISSIONS (ESPECIALLY $NO_x$)
- COMPACT
- QUIET
- HIGH TURNDOWN RATIO

#### VAPOR GENERATOR

- COMPACT
- FAST RESPONSE
- LOW COST
- LOW METAL TEMPERATURES

### GENERAL APPROACH

#### BURNER

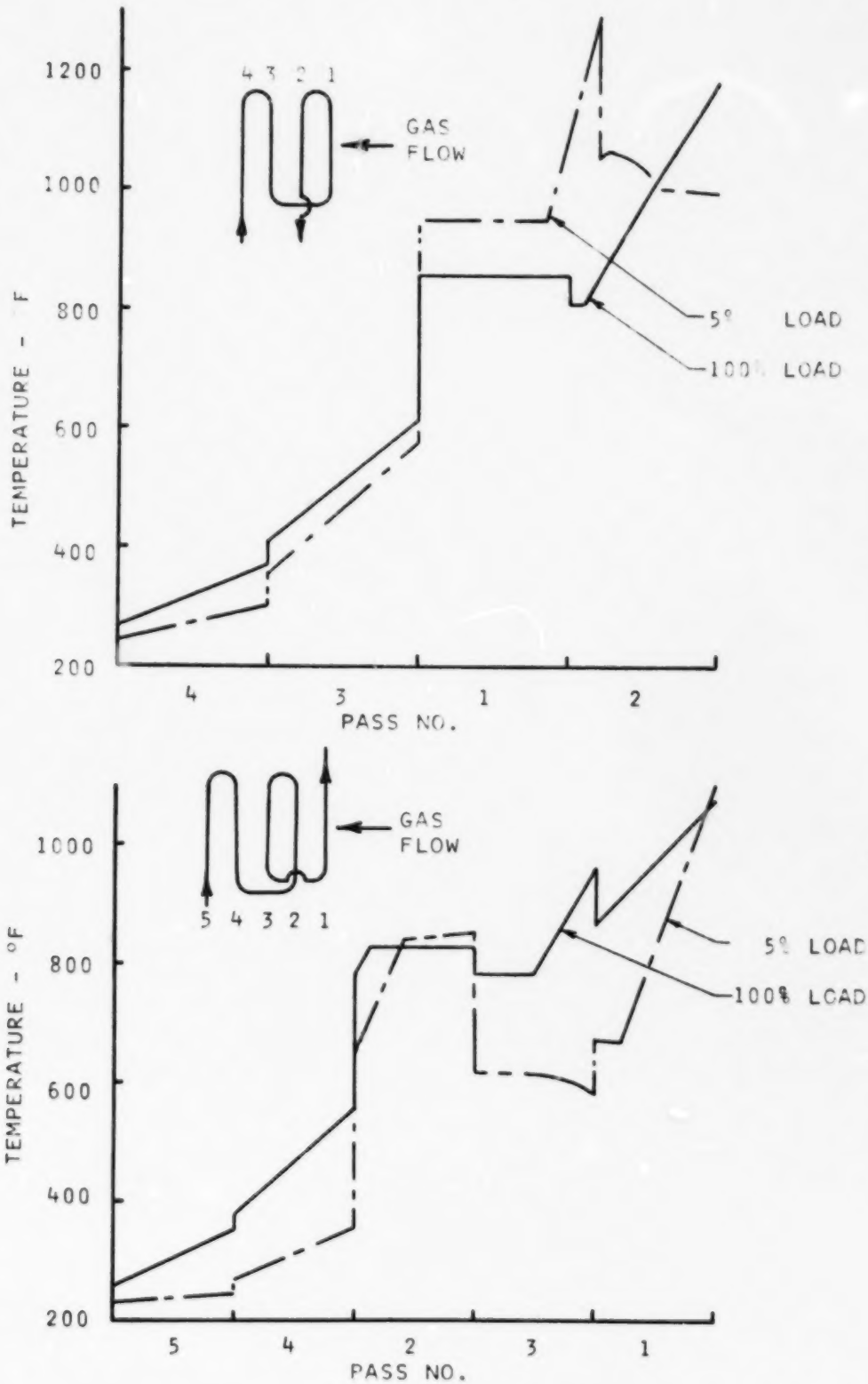
- HOMOGENEOUS COMBUSTION (PREMIXED)
- MULTI-PORT FLAMEHOLDER - LARGE FLAME SURFACE
- QUENCH BEFORE $NO_x$ REACTION COMPLETE
- UNIFORM RESIDENCE TIME
- FUEL VAPORIZATION BY C.G.R.

#### VAPOR GENERATOR

- MONOTUBE / ONCE THRU FLOW
- COILED FINTUBE
- 5-PASS MIXED COUNTER FLOW/PARALLEL FLOW

#### INTEGRATION OF BURNER AND VAPOR GENERATOR

- PROVIDES UNIFORM RESIDENCE TIME
- ENHANCES COMPACTNESS




TUBE WALL TEMPERATURE DISTRIBUTION

## STEAM GENERATOR SPECIFICATIONS

| | |
|---|---|
| FIRING RATE (HHV) | $2 \times 10^6$ BTU/HR |
| NET HEAT INPUT | $1.6 \times 10^6$ BTU/HR |
| BOILER EFFICIENCY (HHV) | FULL LOAD 78%<br>5% LOAD 88% |
| STEAM TEMPERATURE | 1000°F |
| STEAM PRESSURE | 1000 PSIG |
| FEEDWATER TEMPERATURE | 220°F |
| FEEDWATER PRESSURE | 1150 PSIG |
| COMBUSTION GAS PRESSURE DROP | 1.0 IN W.C. |
| MAXIMUM TUBE WALL TEMPERATURE | 1100°F |
| CONFIGURATION | 5 PASS |
| CORE SIZE | 17.5" DIA X 11" |
| CORE WEIGHT | 75.5 LB |
| TUBING LENGTH | 126.4 FT |
| MATERIALS | |
| ECONOMIZER | 44.8 FT, 1/2" OD X 0.065 WALL CARBON STEEL FINTUBE |
| EVAPORATOR | 61.6 FT, 5/8"OD X 0.065 WALL STAINLESS FINTUBE |
| SUPERHEATER | 20 FT, 5/8" OD X 0.065 WALL STAINLESS BARE TUBE |
| DIMENSIONS (INCLUDING BURNER AND INLET DUCTING) | 19.5" DIA X 17" |
| TOTAL WEIGHT (INCLUDING BURNER AND INLET DUCTING) | 150 LB (EST) |

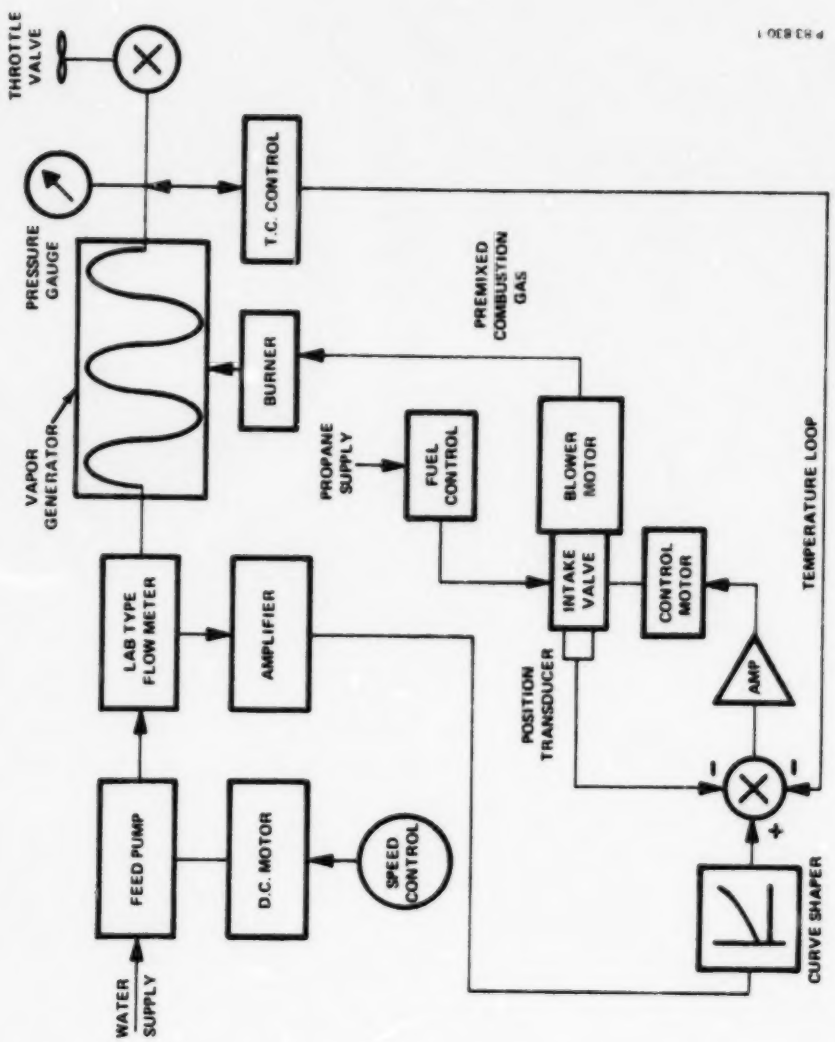
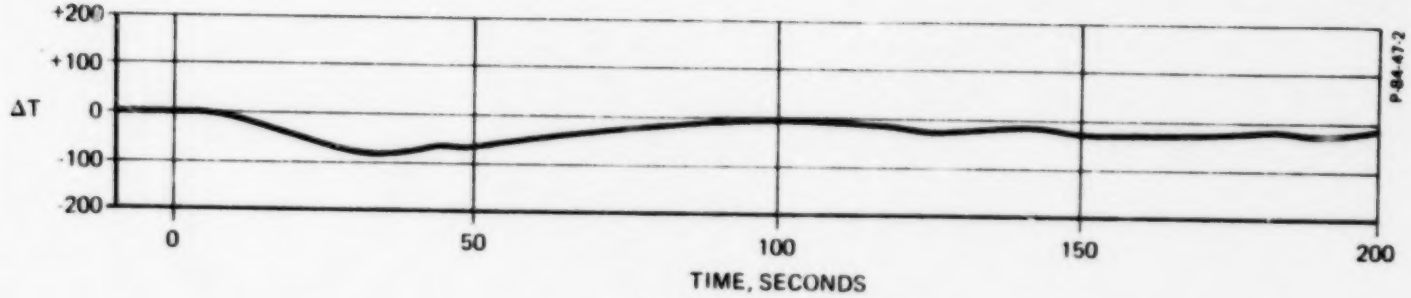
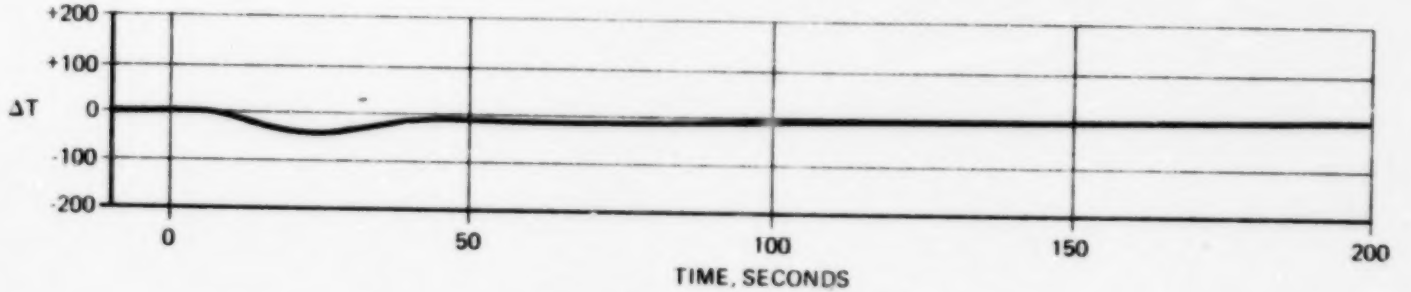



Figure 3-1 - Control Mode Simulation Block Diagram




Experimental Results
SES-4 Steam Generator Manual Pressure Control
Predictive Temperature Control Nominal Setting




Hybrid Computer Results
SES-5 Steam Generator Bypass Pressure Control
Predictive Temperature Control Nominal Setting

Effect of the Step Change From 39 to 56 Percent Flow Level in Steam Throttle Setting on Superheater Outlet Temperature

## BURNER DEVELOPMENT

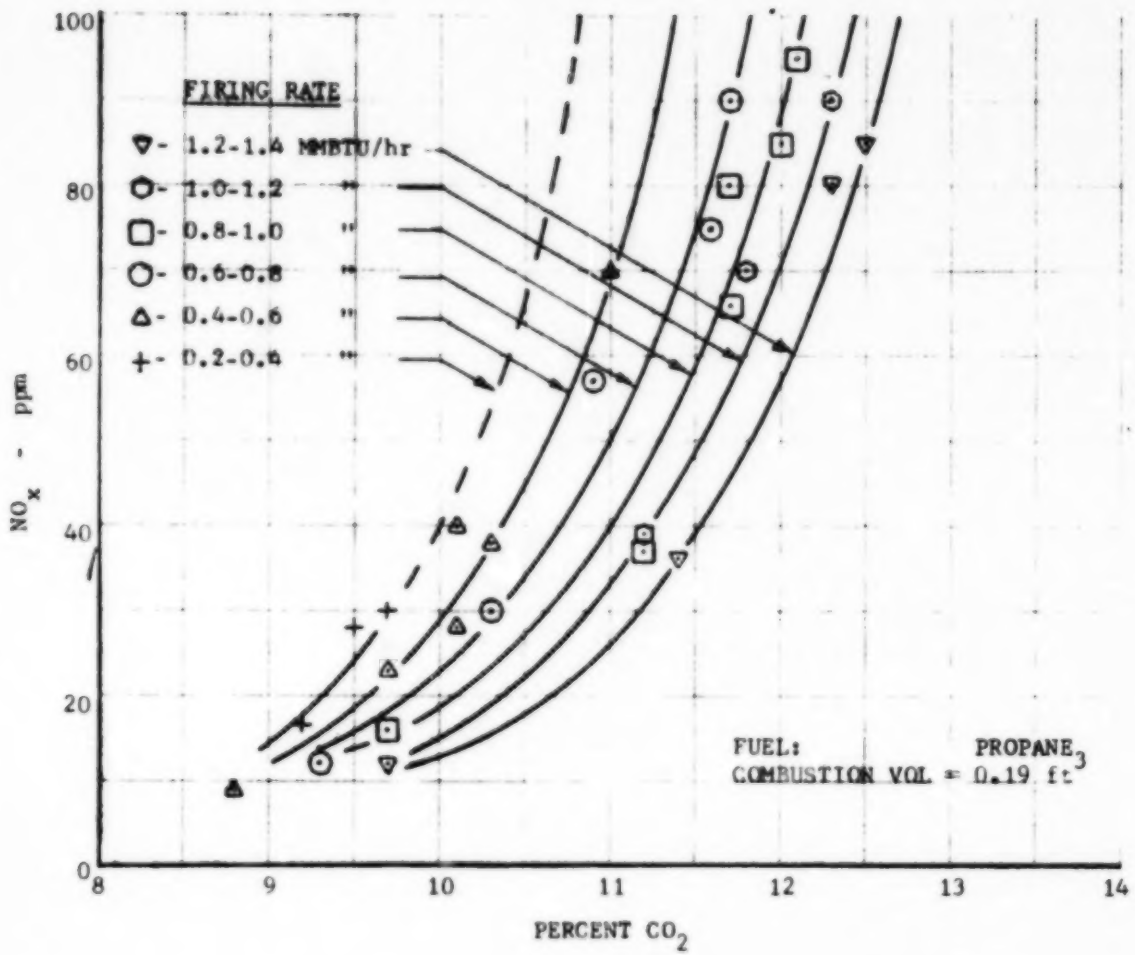
MODEL #4 STEAM GENERATOR HAS BEEN TESTED FOR EMISSIONS AT FIRING RATES TO $1.4 \times 10^6$ BTU/HR USING MULTIPORT FLAMEHOLDER WITH PROPANE. EMISSIONS WERE ALL BELOW EPA GOALS.

**MODEL NO. 4 EMISSIONS**

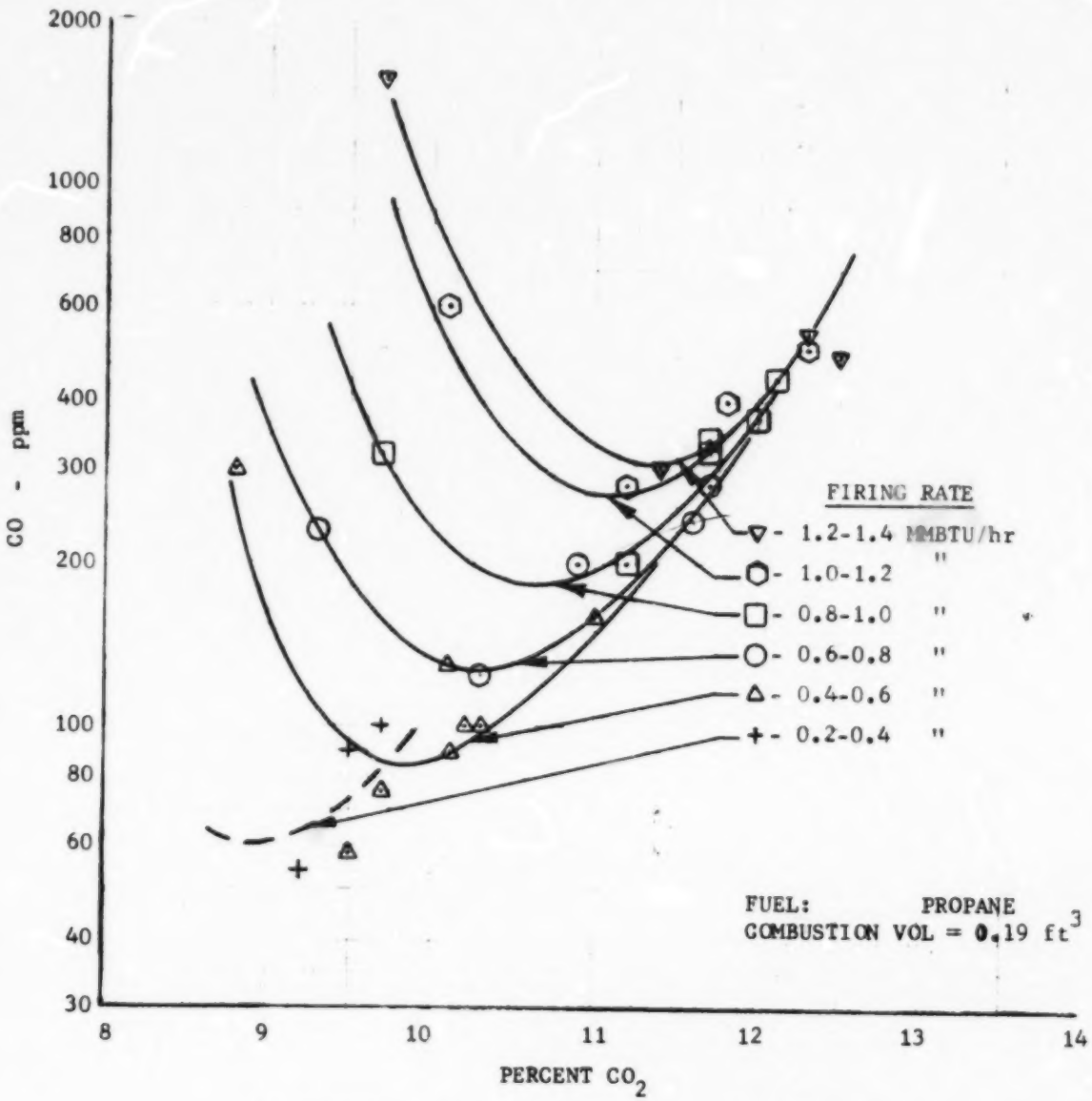
| | MEASURED‡ | EPA GOALS |
|---|---|---|
| UHC - G/MI | 0.03 | 0.14 |
| $NO_2$ - G/MI | 0.2 | 0.4 |
| CO - G/MI | 0.4 | 4.7 |

‡FUEL ECONOMY ASSUMED TO BE 10 MPG

EMISSIONS AT 25% LOAD TAKEN TO REPRESENT DRIVING CYCLE AVERAGE




$NO_x$ EMISSIONS FROM MODEL NO. 4 STEAM GENERATOR




CO EMISSIONS FROM MODEL NO. 4 STEAM GENERATOR

## GASOLINE BURNER

### DESIGN FEATURES

- QUARTER SCALE
- MULTI-PORT FLAMEHOLDER
- FUEL IS EVAPORATED BY COMBUSTION GAS RECIRCULATION
- ATOMIZATION BY PNEUMATIC NOZZLE

### TEST RESULTS

- $NO_x$ AND CO ABOUT THE SAME AS PROPANE-FIRED TEST RESULTS
- HYDROCARBONS INITIALLY WERE HIGH DUE TO POOR MIXING AND UNSTEADY FUEL SUPPLY
- HYDROCARBONS IMPROVED AFTER FUEL SUPPLY PROBLEMS WERE REMEDIED, BUT ONLY FOR EQUIVALENCE RATIOS ABOVE 0.8
- LEAN LIMIT FOR GASOLINE IS NOT AS LOW AS FOR PROPANE
- FOR LOW EMISSIONS UNDER PART LOAD CONDITIONS, BURNER MUST BE ABLE TO OPERATE AT EQUIVALENCE RATIO OF ABOUT 0.7

### PRESENT WORK

- IMPROVE FUEL DELIVERY AND MIXING
- EXTEND LEAN LIMIT FOR GASOLINE